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Strengthening of Timber Beam with Cold-Formed Steel Plates

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Abstract: This paper describes an experimental program which examined the flexural strengthening of timber beams (50x50x1000 mm) using cold-formed steel (CFS) plates (0.75 mm thick and 30 mm wide). A total of fifteen specimens were tested in three-point bending scheme with a span-depth ratio of 18:1. The effectiveness of the steel plates was evaluated for different strengthening lengths and number of strengthening layers. Test results showed that maximum load carrying capacity and stiffness of the strengthened beams can be improved by up to around 70% and 40%, respectively, relative to that of control unstrengthened beams. The increase in the percentage gain occurred as increasing strengthening length as well as number of the strengthening layers. Control unstrengthened beams demonstrated linear elastic behavior during the test whereas the strengthened beams tended to undergo a pseudo-ductile behavior. Along with it tensile failure in timber was still observed in the strengthened beams.

Keywords: Timber beam, steel plates, cold-formed steel, strengthening, flexural, bending test

1. Introduction

Nowadays, timber has been increasingly employed for structural applications in modern civil construction such as multi-storey buildings, public buildings, sports arenas, halls, schools, houses, industrial buildings, as well as bridges for road or pedestrian traffic. As one of the oldest and the most common building materials, timber has many advantageous characteristics. It is well known as a light and strong material. It offers good strength to both compressive and tensile loads (Rescalvo et al. 2018). The other good features of timber include its aesthetic appearance, good fire resistance (Wieczorek et al. 2021), costs effectiveness (Ghazijahani et al. 2017), easy handling and carrying (Dar et al. 2021; Waseem et al. 2022), lower embodied energy (Falk 2010), and high thermal and acoustic insulation (Uzel et al. 2018). And the most importantly, in terms of sustainability, timber is truly environmentally friendly compared to steel, concrete, and other building materials. Its production is part of a life cycle so that, in priciple, it is regenerative. Despite various advantages, because timber is also organic material, it is very likely to undergo deterioration due to aging and natural environmental processes (e.g. humidity and temperature), in addition to biological attacks (e.g. fungi and insects). Deterioration of timber becomes a crucial since the timber is used as structural components in buildings. Therefore, attempts to repair or strengthen the timber are needed so that timber structures can survive and remain safe.

Many literatures are available where the behavior of strengthened concrete or steel elements has been investigated (Yoresta et al. 2020a, 2020b, 2020c, 2021, 2022; Nakamoto et al. 2020; Esfahani et al. 2007; Breveglieri et al. 2014; Sallam et al. 2010). Essentially, strengthening technique is an attempt to cover the weakness of one material with the strength of other additional materials. Researchers have used various types of materials for strengthening timber (Sliker 1962; Valuzzi et al. 2007; Bulleit et al. 1989; Garcia et al. 2013) and the strengthening schemes are also different. Isleyen and Kesik (2021) studied the utilization of carbon fiber reinforced polymer (CFRP) strips to improve the mechanical behaviors of old wood. The reinforcement system showed a positive effect on the bending strength,

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ductility, and energy dissipation capacity of the specimens. Corradi and Borri (2007) strengthened timber beams using pultruded glass fiber reinforced polymer (GFRP). It was indicated from the test that GFRP elements provide strong increase in flexural capacity as well as stiffness of the beams. Gand et al. (2018) evaluated the effect of strengthening of timber beams using basalt fiber reinforced polymer (BFRP) rods. It was found that ultimate load capacity of the beams can be increased by an average of 16%.

The structural response of timber beams strengthened with steel cords was studied by Borri and Corradi (2011). The beams experienced a non-linear behavior and better flexural stiffness and strength after wood yielding in compression. Soriano et al. (2016) used steel bars to reinforce glued-laminated timber beams. The presence of steel bars, besides significantly increasing stiffness, tends to make the mechanical behavior of the glulam beams more uniform (small variations). Jasienko and Nowak (2014) tested timber beams with steel plates as strengthening materials. They revealed that the results obtained were comparable to those reinforcement with fiber reinforced polymers (FRP) materials. In another study, Borri et al. (2013) used natural fiber based composite materials, made from hemp, flax, basalt, and bamboo fibers, for strengthening of timber beams. The use of the natural fiber composites is more effective for timber beams with poorer mechanical properties (low-quality). The possibility of using bamboo scrimber as strengthening material for timber beams was evaluated by Chen et al. (2021). Their findings also revealed that ductility of the beams can be well improved. Besides, the gain in maximum capacity varied from 20% to 70% and stiffness from 40% to 160%.

In this paper, another alternative method of strengthening timber beams using cold-formed steel (CFS) is presented. Cold-formed steel is lightweight, ease of installation, high tensile strength, and corrosion resistance. It is also currently widely available and can be easily obtained in market in Indonesia at affordable price. Literatures are available on the strengthening of timber beams with CFS elements, but the numbers are still very limited and mostly focusing on using CFS sections (Ardhira and Syriac 2019; Awaludin et al. 2015). Reinforcement with CFS sections is still considered less effective as it requires dimensions of timber beams to be similar with the dimensions of CFS sections so that the CFS can be installed. Therefore, as another approach, this research aims to investigate the structural behavior of timber beams strengthened with CFS plates which is possible to be applied to all types of timber beams. Through this purpose, experimental test is performed with variable length of strengthening and number of layers of CFS plates. The maximum load carrying capacities of the beams, initial stiffness responses, load versus deflection at midspan behavior, and failure mechanisms obtained from experiment are analyzed and discussed.

2. Experimental Program

This experimental program consisted of flexural testing 15 timber beam specimens (50x50x1000 mm) under static loading. The strengthened specimens are divided into four types based on strengthening length, namely 360 mm (type A), 540 mm (type B), and 630 mm (type D), which respectively correspond to 40%, 60%, and 70% of the beam span (900 mm). Strengthening of the beams is performed at middle span using one layer of cold-formed steel plate. However, in order to allow for the investigation on strengthening effect due to difference in number of strengthening layers, the beam with 540 mm strengthening length is also prepared with two strengthening layers, hereinafter reffered to as specimen type C. Details of specimens are summarized in Table 1 and the outline is shown in Fig. 1.

The timber beams are made from Red Meranti (Shorea leprosula Miq.) (Fig. 2). This species of timber is assigned strength class III based on Indonesian timber regulation (PKKI-NI5 1961). Material properties are obtained in accordance with Standard Test Methods for Small Clear Specimens of Timber (ASTM D143-22). The average flexural strength and average compression strength parallel to grain of the Red Meranti are recorded as 39.7 MPa with a standard deviation of 6.0 MPa and 21.8 MPa with a standard deviation of 4.4 MPa, respectively. The average moisture content is 10.8% (standard deviation 0.4%). Besides, the CFS plate for reinforcement has a minimum yield strength of 550 MPa with 0.75 mm thick according to manufacturer data.

Strengthening timber beams are conducted by attaching CFS plate at bottom side of the beam using 16 mm length self drilling screws. The CFS plate used is a part of web in CFS (C75.75) sections which is cut into 30 mm wide and the length as determined in Table 1. All the beams including control unstrengthened ones are tested with three repetitions in three-point loading scheme using Universal Testing Machine (UTM) Instron with a capacity of 50 kN. During the test, load and deflection are recorded through the machine. Fig. 3 shows photograph of the test setup.

Table 1 - Specimen details

Type	Specimen length (mm)	CFS length (mm)	CFS percentage of span length (%)	CFS layers	Repetition
N	1000	-	-	-	3
A	1000	360	40	1	3
B	1000	540	60	1	3
C	1000	540	60	2	3
D	1000	630	70	1	3

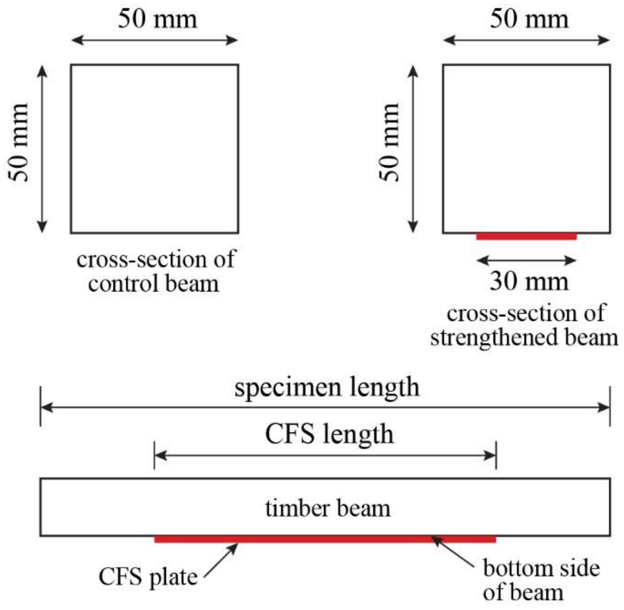

Fig. 1 - Dimension and configuration of test specimen

Fig. 2 - Red Meranti timber rafters

Fig. 3 - Beam test setup

3. Results and Discussion

A summary of the test results is given presented in Table 2. The results are given for each specimen, namely maximum load capacity and flexural stiffness of the beams. Along with these data, the average values as well as standard deviations for each group of the beam specimens are also presented. Then, the percentage gain in maximum load capacity and flexural stiffness for the strengthened beam type A, B, C, and D is included as a comparison to the control beams (Type N).

Table 2 - Summary of test results

Type	Specimen		Max. Load P_{max} (N)	Stiffness EI (N.mm^2 x 10^9)
N	N-1		2523.5	2.09
	N-2		2157.6	1.89
	N-3		2193.6	2.00
		Ave.(St.dev.)	2291.6 (201.7)	1.99 (0.10)
A	A-1		2994.3	2.12
	A-2		2313.9	1.85
	A-3		2622.7	2.06
		Ave.(St.dev.)	2643.6 (340.7)	2.01 (0.14)
		Percent gain (%)	15.4	1.0
B	B-1		3604.9	2.21
	B-2		3508.9	2.36
	B-3		3351.9	2.38
		Ave.(St.dev.)	3488.6 (127.7)	2.32 (0.09)
		Percent gain (%)	52.2	16.2
C	C-1		4008.8	2.91
	C-2		3442.7	2.41
	C-3		4315.3	2.56
		Ave.(St.dev.)	3922.3 (442.7)	2.63 (0.26)
		Percent gain (%)	71.2	31.8
D	D-1		3329.4	2.67
	D-2		4316.0	3.11
	D-3		3441.6	2.57
		Ave.(St.dev.)	3695.7 (540.2)	2.78 (0.29)
		Percent gain (%)	61.3	39.5

3.1 Strengthening Effect

The percentage gain in maximum load capacity (η) of the strengthened beams (beam type A, B, C, and D) relative to the control beams (type N) showed in Table 2 is based on Eq. (1). In Eq. (1), $P_{\mathrm{max,ave},i}$ means the average values of maximum load for the strengthened beams i (i = beam type A to D) and $P_{\mathrm{max,ave,N}}$ represents the average value of maximum load for the control beams (type N).

$$\eta = \frac{P_{\mathrm{max,ave},i} - P_{\mathrm{max,ave,N}}}{P_{\mathrm{max,ave,N}}} \times 100\% \qquad (1)$$

It is very clear from Table 2 that strengthening using cold-formed steel plate provides positive strengthening effect. The percentage gain in maximum load capacity varied within the range of 15.4%-71.2%. The lowest value is attained in beam type A but the highest one is found in beam type C. It can also be confirmed that the values of the percentage gain increase as increasing length of CFS plate utilized. This condition can be clearly captured from beam type A, B, and D where the steel length is 40%, 60%, and 70% of the beam span length, respectively. Nevertheless, beam type C with also steel plate 60% of the beam span length, has the highest percentage gain compared to that of other strengthened beams. This may indicate that maximum load capacity of the timber beams can be improved more effectively by using more layers of CFS plates.

3.2 Load-Deflection Behavior

The relationship curve between applied load and deflection at mid-span of all tested beams is shown in Fig. 4 to Fig. 8. Basically, the figures graphically confirm the improvement in the performance of the strengthened beams. Maximum load capacity of the strengthened beams, especially with 60% and 70% strengthening lengths, is significantly improved (>50%) compared to the unstrengthened ones. It can be seen from Fig. 4 that the control unstrengthened beams demonstrate a linear elastic behavior where the slope of the load-deflection curve is relatively constant from the beginning step of loading up to failure. However, on the beams with CFS plates strengthening (Fig. 5 to Fig. 8), with a very slightly steeper curve than that of control beam, the slope of the curve reduces when reaching a certain load and it continues until maximum load at a larger deflection. This finding may indicate that the strengthened beams undergo a pseudo-ductile beam behavior, particularly beam A-1 (Fig. 5), C-3 (Fig. 7), and D-2 (Fig. 8).

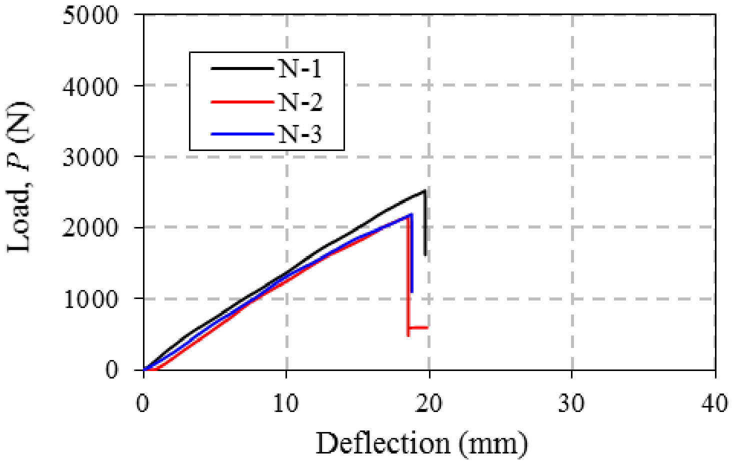

Fig. 4 - Load-deflection behavior for control unstrengthened beams (type N)

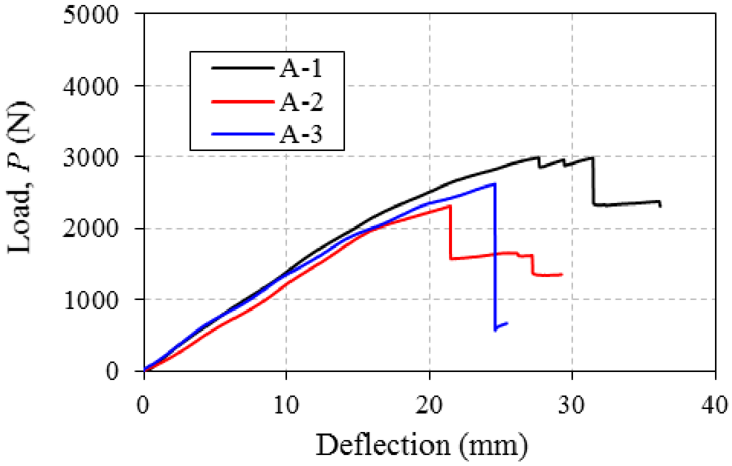

Fig. 5 - Load-deflection behavior for CFS plate strengthened beams (type A)

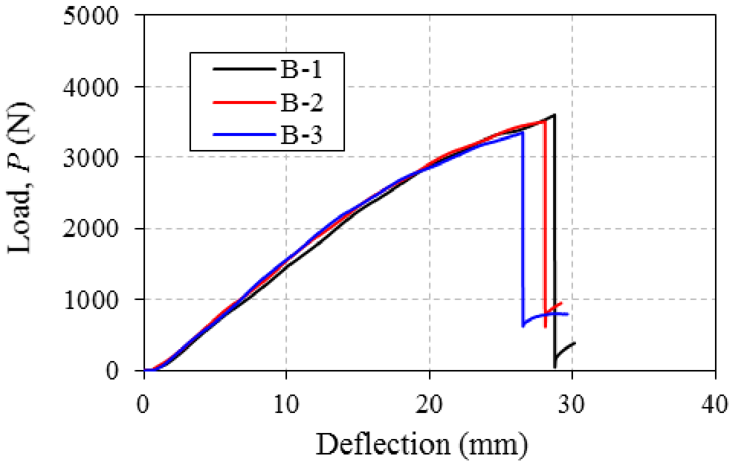

Fig. 6 - Load-deflection behavior for CFS plate strengthened beams (type B)

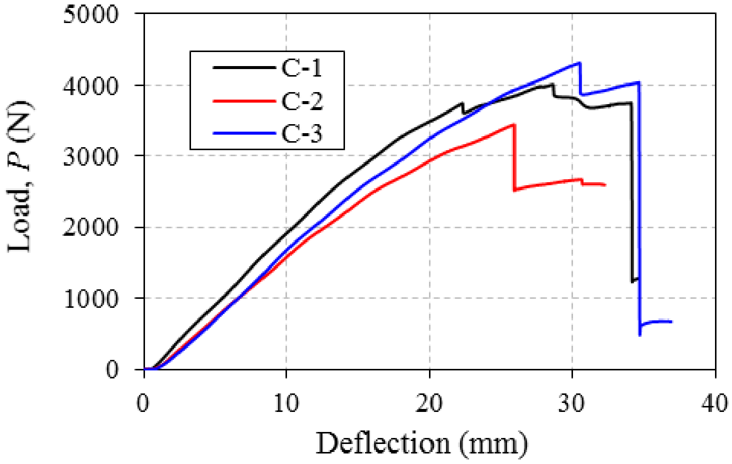

Fig. 7 - Load-deflection behavior for CFS plate strengthened beams (type C)

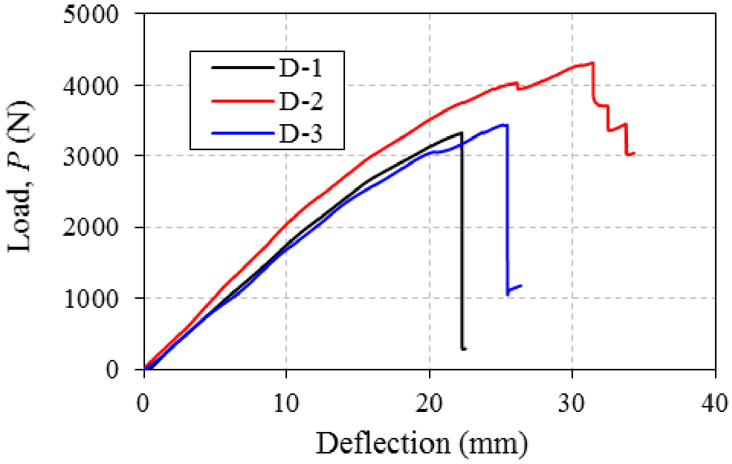

Fig. 8 - Load-deflection behavior for CFS plate strengthened beams (type D)

3.3 Stiffness Response

Stiffness is calculated from the linear-elastic part of the load-deflection curve of each beam using Eq. (2). In this equation, ΔP denotes the given range of applied load; L is span length; $\Delta\delta$ is the range of deflection corresponding to the load range ΔP; and, E and I refer to modulus of elasticity and moment of inertia respectively.

$$EI = \frac{\Delta P L^3}{48\Delta\delta} \qquad (2)$$

It can be seen from the calculation results summarized in Table 2 that strengthening using CFS plate has increased the stiffness of the timber beams. The stiffness of the strengthened beams type A, B, C, and D, based on the average values of the three similar specimens in each type, is improved by 1.0%, 16.2%, 31.8%, and 39.5%, respectively compared with control unstrengthened beams (type N). The variation of these values at once confirm that increasing in the number of strengthening layers (beam type B and C) and the strengthening length (beam type A, B, and D) has a proportional effect on the increasing percentage gain in stiffness of the beams. However, it is also interesting to note that this fact is clearly observed in the use of CFS plate with length of more than 40% of the beam span. The findings within this study prove that the beam type A with strengthening length of 40% of the beam span has a very small change in stiffness, i.e., 1.0% (see Table 1) so that it can be categorized as having no significant increase in the flexural stiffness, or in other words the stiffness is still similar or remain unchanged compared to that of control beams.

3.4 Typical Failure Modes

Typical failure modes of all tested beams are shown in Fig. 9. The control unstrengthened beams suffer a brittle tensile failure at bottom side of the beam (Fig. 9a). A tensile-flexural failure in timber is still observed in almost all specimens of the strengthened beams, as shown in Fig. 9b. However, there is one beam experiencing shear failure in timber, namely D-1. Crack in the timber is initiated near one end of the steel plate and then propagate across the timber horizontally, as shown in Fig. 9c. Fig. 9d exhibits another mode of failure experienced by all strengthened beams. The higher tensile stress at bottom side of the beam tend to make self-drilling screw located at the ends of CFS plate pulled out. Nevertheless, according to observation it can be confirmed that no damage at all can be found on the CFS plate.

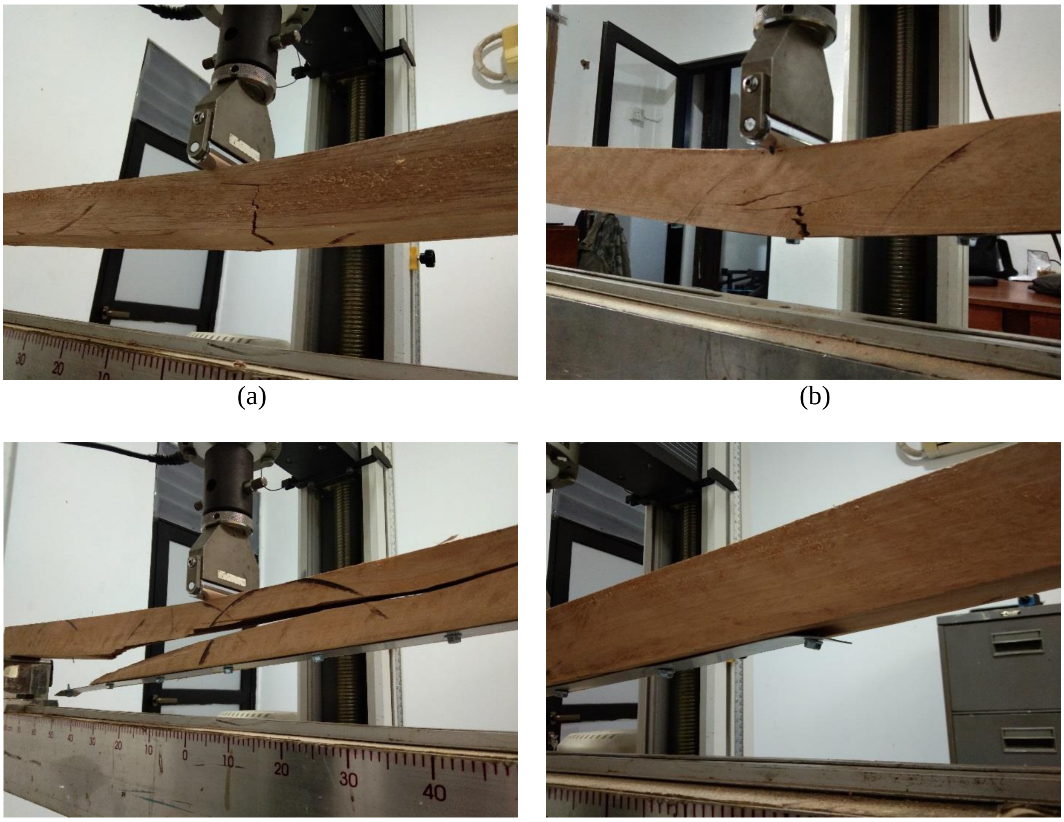

Fig. 9 - Failure modes of tested beams (a) brittle failure in control beams; (b) tensile-flexural failure in strengthened beams; (c) shear failure in strengthened beam; (d) screw pulled out at the end of CFS plate

4. Conclusions

The experimental investigation results demonstrated that the use of cold-formed steel plates could be an effective way for enhancing performance of timber beams. The maximum load carrying capacity of timber beams could be improved within the range of 15.4% and 71.2%. In addition, the stiffness of the timber beams was also increased by up to about 40%. The improvement of the load carrying capacity and stiffness of the beams was influenced by the parameter of length and number of CFS layers. The beams with longer CFS length or greater number of CFS layers had the higher level of performances. The results also showed that the strengthened beams tended to undergo a pseudo-ductile behavior in comparison of the linear elastic behavior of the control unstrengthened beams. Damage was mostly found in timber and in the form of tensile failure.

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